

# Assault on the Nastiest Effective Operator at the LHC

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Higher-dimensional multi-gluon interactions affect essentially all effective Lagrangian analyses at the LHC. We show that, contrary to common lore, such operators are best constrained in multi-jet production. Our limit on the corresponding new physics scale in the multi-TeV range exceeds the typical reach of global dimension-6 Higgs and top analyses. This implies that the pure Yang–Mills operator can safely be neglected in almost all specific higher-dimensional analyses at Run II.

With the first analyses of Run II data of the LHC appearing, effective Lagrangians [1, 2] are rapidly developing into the main physics framework describing searches for physics beyond the Standard Model. Global analyses of Run I and early Run II data already exist for the Higgs and electroweak gauge sectors [3] and for the top sector [4], illustrating the power of this approach. The fact that essentially all production processes in all physics sectors involve incoming gluons poses a major, unsolved challenge to all such effective Lagrangian analyses: the pure Yang–Mills operator with its corresponding Wilson coefficient

$$c_G \mathcal{O}_G = \frac{g_s^2 c_G}{\Lambda^2} f_{abc} G_{a\nu}^\rho G_{b\lambda}^\nu G_{c\rho}^\lambda$$

with  $G_a^{\rho\nu} = \partial^\rho G_a^\nu - \partial^\nu G_a^\rho - ig_s f_{abc} G^{b\rho} G^{c\nu}$  (1)

will correlate all such analyses [5, 6] and force us into an unwieldy, if not unrealistic, global analysis of all LHC channels. The operator  $D^\mu G_{\mu\nu} D_\rho G^{\rho\nu}$  can lead to similar effects, but it can be removed from our operator basis through equations of motion, mapping it to four-quark operators [7].

It is very well known that the contribution of  $\mathcal{O}_G$  to di-jet production in gluon-gluon or gluon-quark scattering does not interfere with the Standard Model process [8]. Heavy quark production,  $gg \rightarrow t\bar{t}$  is an exception, and it can be used to constrain  $c_G/\Lambda^2$  at the Tevatron [7]. However, the operator  $\mathcal{O}_G$  is only one of many operators contributing to top pair production, giving marginalized Run I constraints of the order  $\Lambda/\sqrt{c_G} \gtrsim 850$  GeV [4]. Alternative, but less powerful search strategies include four-jet production at LEP [9] and three-jet production at hadron colliders [10], while the suggestion to constrain  $\mathcal{O}_G$  in a Higgs analysis [11] lacks realism given the current reach of such a Higgs analysis [3].

In this letter we propose to search for effects of  $\mathcal{O}_G$  in a new channel, namely multi-jet production which we analyze for up to six hard jets. Our analytic understanding

of inclusive and exclusive multi-jet production processes has matured [12], and we can robustly and precisely simulate such processes [13]. In this note we will rely on two well-controlled observables, namely the (exclusive) number of jets  $N_{\text{jets}}$  and  $S_T$ , defined as the scalar sum of jet transverse momenta plus any missing transverse energy exceeding 50 GeV [14],

$$S_T = \left( \sum_{j=1}^{N_{\text{jets}}} E_{T,j} \right) + (\cancel{E}_T > 50 \text{ GeV}) . \quad (2)$$

The two observables allow the separation of two-jet production from events with a larger number of jets while simultaneously giving a measure of the energy scale tested in the partonic process.

Two-jet production from partonic processes such as  $q\bar{q} \rightarrow q'\bar{q}'$  serves as an excellent probe of four-quark effective operators. Because this topology carries little sensitivity to  $\mathcal{O}_G$  [8] we will impose the corresponding ATLAS limits on four-quark operators [15] in our multi-jet analysis in order to limit the effect of these operators.

Our effective Lagrangian hypothesis is defined by following the standard approach of global effective Lagrangian analyses [3, 4] to test the dimension-6 Lagrangian only as a well-defined hypothesis. The effect of the corresponding dimension-6 operators in generic multi-jet signatures scales like  $E^2/\Lambda^2$ , but the wide available energy range at the LHC sheds some doubt on the assumption that the effects of dimension-8 operators are systematically suppressed compared to dimension-6 operators. We therefore treat the effects of higher-dimensional operators as theoretical uncertainties in the matching procedure of a given full model to the dimension-6 Lagrangian [16].

**Multi-jet signature** — Our analysis of the dimension-6 QCD Lagrangian is based on a CMS search for extra-dimensional black holes [14], which to date is the only

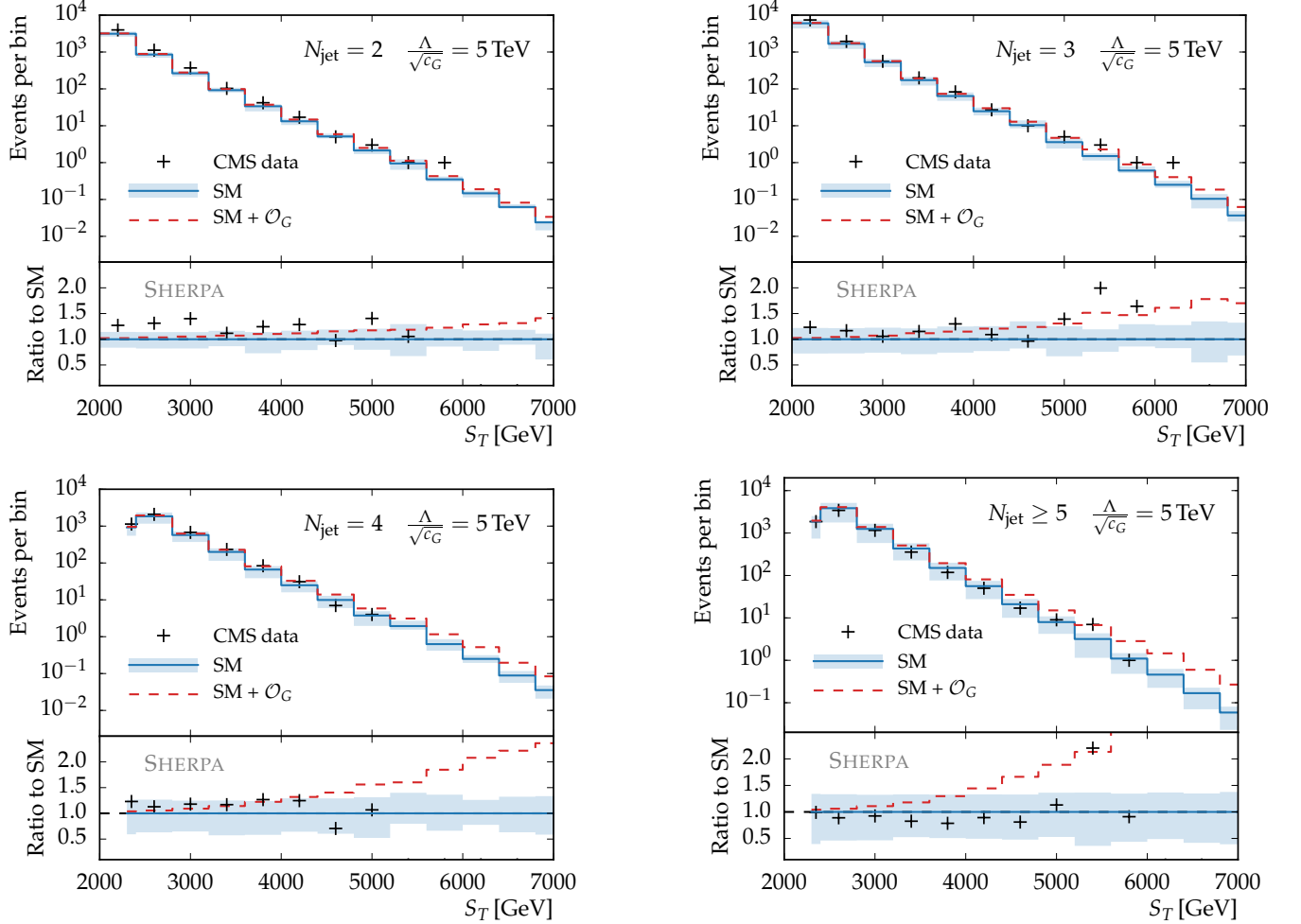


Figure 1:  $S_T$  distributions from CMS [14] in various bins of exclusive/inclusive jet multiplicity  $N_{\text{jets}}$ , compared to our multi-jet-merged signal and background predictions including perturbative uncertainties.

published 13 TeV analysis based on a sizeable data set and extending to a large number of jets without requiring any additional particles in the final state. Obviously, dedicated ATLAS or CMS analyses of multi-jet production in the light of dimension-6 operators will improve upon our results. The background is completely dominated by QCD jet production, so just as in the original analysis we neglect non-QCD backgrounds.

For a robust description of the high-multiplicity QCD jet backgrounds, we employ CKKW multi-jet merging within SHERPA [17, 18], with next-to-leading order matrix elements for di-jet production and leading-order matrix elements for up to six jets in the final state. Our nominal choice for the factorization and renormalization scales is determined by a backwards clustering procedure and the scale choice  $\sqrt{2}\mu_{r,f}^2 = 1/(s^{-1} + t^{-1} + u^{-1})$  for the  $2 \rightarrow 2$  core process [17].

As shown in Fig. 1, the observed  $S_T$  distributions are accurately described by our SM simulations. We estimate perturbative uncertainties through independent variation of both scales by a factor of two around the nominal

values, omitting combinations where one scale is varied upwards and the other one downwards to avoid large logarithms. All differences between data and the SM simulation are within the estimated perturbative uncertainties. The minimal tension in the exclusive two-jet bin at low  $S_T$  only occurs after translating the original inclusive results into jet-exclusive distributions. They will not affect our analysis of the multi-jet rates and our constraints on higher-dimensional operators contributing to this process.

Our signal simulations including the operator  $\mathcal{O}_G$  are based on an implementation of the dimension-6 operator of Eq.(1) in FEYNRULES [19]. We employ the UFO output format in order to facilitate event generation with SHERPA and its matrix element generator COMIX [20, 21]. For the purpose of implementing the new exotic color structures that appear in the Feynman rules of the dimension-6 operator, a code generator module for arbitrary color structures was implemented in SHERPA. This feature will become publicly available along with the next SHERPA release. The automatic generation of

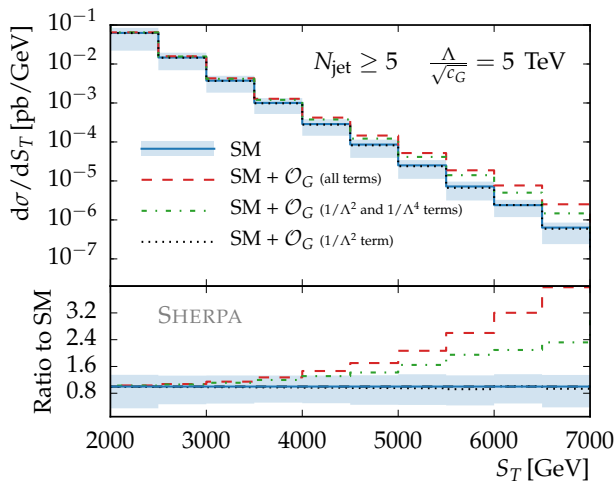


Figure 2: Effect of multiple occurrences of the dimension-6 Yang-Mills operator in the multi-jet matrix elements.

arbitrary Lorentz structures using SHERPA is described in Ref. [21].

Just like the QCD background we compute the contributions of the dimension-6 operator of Eq. (1) using CKKW multi-jet merging techniques with leading order matrix elements for up to five jets [17]. Formally, we can organize the effect of the higher dimension contributions in terms of the scale suppression in the multi-jet cross section. In this scheme, the leading interference terms with SM diagrams are proportional to  $1/\Lambda^2$ , while the dimension-6 contributions squared contribute to  $1/\Lambda^4$  or higher, depending on the numerically relevant number of operator insertions.

In Fig. 2 we show the new physics effects in the  $S_T$  distribution for large jet multiplicities. The effects due to interference terms proportional to  $1/\Lambda^2$  are negligible throughout the displayed range of  $S_T$ . Significant effects arise from terms of order  $1/\Lambda^4$ . For  $S_T > \Lambda$ , the contributions due to multiple insertions of the effective operator which are beyond  $1/\Lambda^4$  become dominant. In this region, the deviations from the Standard Model generally become very large. This is expected from simple power counting and might lead to problems in matching our effective Lagrangian results to a given full model. There are two standard ways to modify to our original hypothesis: first, we can truncate the  $S_T$  spectrum at  $S_T \gtrsim \Lambda$ . Such a cut is known to almost essentially remove the sensitivity to higher-dimensional operators for example in Higgs physics [3]. Second, we can expand the differential cross section in addition to the Lagrangian and truncate the cross section at  $1/\Lambda^4$ . In our analysis, we retain comparable sensitivity in both approaches, because our reach in  $\Lambda/\sqrt{c_G}$  will largely be determined by the maximum partonic energy  $S_T$  available in the analysis.

Four-quark operator — While multi-jet production at

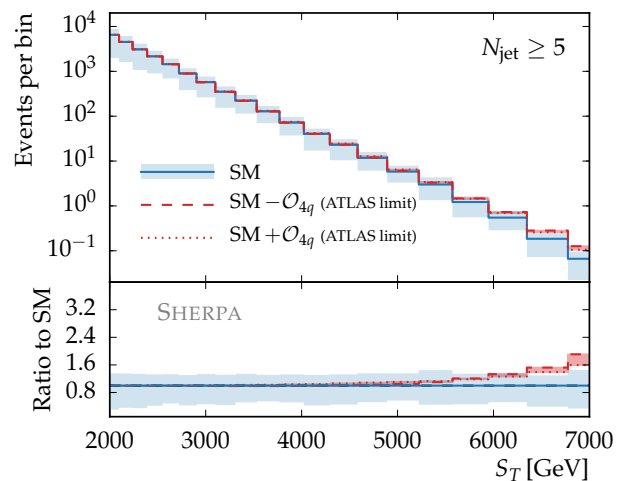


Figure 3: Effect of effective four-quark operators in our signal region, with  $\Lambda/\sqrt{c_{q4}}$  set to the lower limits obtained by ATLAS [15].

the LHC is dominated by gluon amplitudes, processes with quarks in the initial and final states still lead to visible effects. These processes are sensitive to the dimension-6 contact interaction

$$c_{q4}\mathcal{O}_{q4} = \pm \frac{c_{q4}}{\Lambda^2} \sum_{q,q'} (\bar{q}_L \gamma^\mu q_L) (\bar{q}'_L \gamma^\mu q'_L) . \quad (3)$$

While in principle the two operators in Eq.(1) and Eq.(3) should be treated concurrently, we know from the amplitude structure that the number of jets  $N_{\text{jets}}$  separates their respective signal regions. For the four-quark operator the highest sensitivity can be obtained from two-jet correlations and we therefore use the state-of-the-art result from the comprehensive, multi-variate ATLAS analysis [15]. Being formulated as an extension to resonance searches it does not include the higher-dimensional gluon operator, and one should therefore use the two-jet topology only. There, the ATLAS analysis gives

$$\frac{\Lambda}{\sqrt{c_{q4}}} > 4.79 \dots 6.8 \text{ TeV} , \quad (4)$$

in the conventions of Eq.(3) and depending on the assumed sign of the Wilson coefficient.

We estimate the impact of the four-quark operator on our Yang-Mills analysis by computing its effect on multi-jet production. In Fig. 3 we show the impact of the four-quark operator within its allowed range of Eq.(4) on the multi-jet signature. This result can be directly compared to the expected signal from  $\mathcal{O}_G$ , shown in Fig. 2.

Comparing the two effects on the high-energy tail of the  $S_T$  distribution with an assumed new physics scale  $\Lambda/\sqrt{c_G} \lesssim 5$  TeV we confirm that the four-quark effects are strongly suppressed. We find that the two effects only become comparable when we increase the new physics scale in the Yang-Mills operator to  $\Lambda/\sqrt{c_G} \gtrsim 7$  TeV.

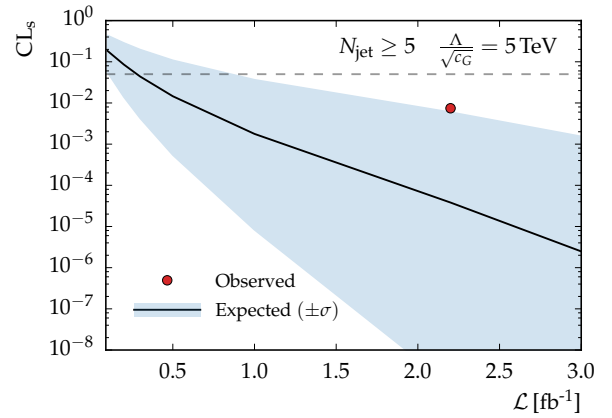
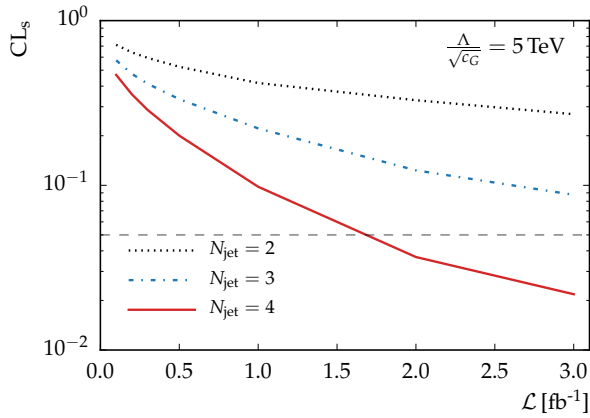


Figure 4: Observed and expected signal confidence levels as a function of the integrated luminosity. We show the expected results for fixed numbers of  $N_{\text{jets}} = 2, 3, 4$  (left) and for  $N_{\text{jets}} \geq 5$  (right). An observed  $\text{CL}_s$  below the dashed line indicates a signal confidence below 5% and allows for an exclusion of the dimension-6 hypothesis.

Multi-gluon operator limit — Finally, we can use the  $S_T$  distributions in bins of  $N_{\text{jets}}$  to constrain the Yang–Mills operator  $\mathcal{O}_G$  in terms of a signal confidence  $\text{CL}_s$  as defined in [22]. In the calculation of  $\text{CL}_s$  we take into account the dominant systematic uncertainties, which are inherent in our background predictions. In Fig. 4 we show the expected signal confidence for  $\Lambda/\sqrt{c_G} = 5$  TeV as a function of the integrated luminosity collected at the LHC with  $\sqrt{s} = 13$  TeV. In the left panel we see that indeed the sensitivity of the two-jet topology is poor. This also confirms that adding the Yang–Mills operator  $\mathcal{O}_G$  to the four-quark operator analysis of ATLAS will not affect the limit shown in Eq. (4).

For higher jet multiplicities  $N_{\text{jets}} = 3, 4$  the LHC reach slowly increases, and we expect to rule out  $\Lambda/\sqrt{c_G} < 5$  TeV based on an integrated luminosity of less than  $2 \text{ fb}^{-1}$ . However, the by far strongest constraints can be derived from the inclusive five-jet sample, with a required luminosity well below  $0.5 \text{ fb}^{-1}$  for  $\Lambda/\sqrt{c_G} = 5$  TeV.

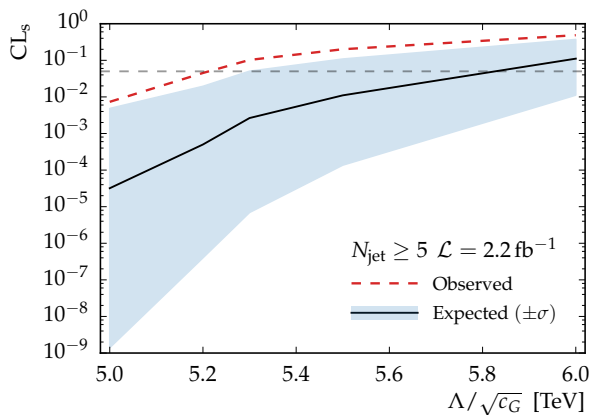


Figure 5: Observed and expected signal confidence levels for the Yang–Mills operator  $\mathcal{O}_G$  as a function of  $\Lambda/\sqrt{c_G}$ .

In the conventions of Eq.(1) we find a limit on the Yang–Mills operator  $\mathcal{O}_G$  of

$$\begin{aligned} \frac{\Lambda}{\sqrt{c_G}} &> 5.2 \text{ TeV} && \text{(observed)} \\ \frac{\Lambda}{\sqrt{c_G}} &> 5.8 \text{ TeV} && \text{(expected),} \end{aligned} \quad (5)$$

based on  $\text{CL}_s < 5\%$ . The difference between expected and observed limits corresponds to a deviation of just over one sigma and is due to a slight excess in the data between  $S_T = 5$  TeV and  $S_T = 6$  TeV, as shown in the lower right panel of Fig. 1.

Conclusions — The purely gluonic dimension-6 operator  $\mathcal{O}_G$  is known to be a major problem for all effective Lagrangian analyses at Run II. We show, for the first time, that it can very effectively be constrained using multi-jet signatures at the LHC. Based on a CMS black-hole search with an integrated luminosity of  $2.2 \text{ fb}^{-1}$  at 13 TeV we find a limit  $\Lambda/\sqrt{c_G} > 5.2$  TeV. For an alternative definition  $\mathcal{O}_G = 1/\Lambda^2 f_{abc} G^3$  without the additional factor of  $g_s$ , we find  $\Lambda/\sqrt{c_G} > 4.7$  TeV.

The effect of four-quark operators on our analysis can be fully controlled by considering the two-jet and multi-jet signatures separately. Our analysis demonstrates that possible effects of this operator can be safely neglected in specific effective Lagrangian analyses for example of the gauge, Higgs, or top sectors.

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